

On The Origin of HI in Galaxies: The Sizes and Masses of HI Photodissociation Regions

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Abstract. Young stars in the disks of galaxies produce HI from their parent H₂ clouds by photodissociation. This paper describes the observational evidence for and the morphology of such HI. Simple estimates of the amount of dissociated gas lead to the startling conclusion that much, and perhaps even all, of the HI in galaxy disks can be produced in this way.

1. Introduction

Most observers view the clouds of HI we see in galaxies as the raw material out of which the stars were formed. These clouds are thought to form higher-density complexes of gas and dust, turn molecular (H₂), and then form stars. In this context, the observed correlation between the star formation rate in galaxy disks and the HI content (often called the Schmidt Law) is generally viewed as being at the basis of an understanding of the global star formation process in galaxies. However, after many years of work to elucidate the specific physics of this process, we have a complicated and still rather rudimentary picture of just how all this might happen.

I want to propose a different view for a part of this “star-formation” story. This view is contrary to the conventional wisdom, but it has the virtue of being physically much simpler. I hope to convince you that this view is supported both qualitatively, by the detailed morphology of the HI observed in galaxy disks, as well as quantitatively, by the theory of photodissociation of H₂. In this view, the basic star construction material in galaxies is gas which is already mostly molecular, and out of which the stars form directly. HI appears in the region when the leftover H₂ is illuminated with UV photons from nearby young stars. The physics of photodissociation regions provides a natural and quantitative explanation for the appearance of HI envelopes around the clouds, and for the CO(1-0) emission which is sometimes seen emanating from the warmer, higher-density parts of their surfaces. The rather surprising new result is that the total amount of Far-UV emission produced in galaxy disks by run-of-the-mill, non-ionizing B stars is actually sufficient to account for most, and perhaps even all, of the HI present.

2. Background

For me, the first example of failure of the conventional wisdom about HI being the precursor to star formation appeared in the early VLA-HI synthesis images of the relatively nearby galaxy M83, which I first saw at an afternoon seminar given by Mark Ondrechen at the Kapteyn Laboratory in Groningen in 1985. The morphology of the HI in the spiral arms of this galaxy did not fit the expected picture; rather than coinciding with the dust lanes as markers of the highest gas column density, the HI ridges appeared to be shifted to larger galactocentric distances and to correspond better with the line of HII regions marking the locus of the youngest stars in the spiral arm. The density wave picture for spiral structure introduced by Lin & Shu (1964) led to a simple explanation (Roberts 1969) for the separation of the arm of maximum gas column density (located upstream in the flow) and the HII regions (downstream) in terms of the flow velocities and the time to convert the H_2 in GMCs into stars. But if the HI was a precursor to the H_2 in GMCs, this picture did not explain why the HI ridge also appeared downstream with the HII regions. The explanation we offered (Allen, Atherton, & Tilanus 1986) was that the ISM was changing its physical state as it moved along, and doing so in a big way. Primarily molecular to start with, the residual gas after star formation becomes atomic as it is bathed in UV photons from the most massive of the nearby newly-formed stars. It later returns to the molecular form after the young stars die off and the UV flux decreases.

Other studies have followed on M83 and on other nearby spirals (M51, M100) and have generally reached the same conclusions; a list of relevant references is given in the introduction to the paper on photodissociation in M101 by Smith et al. (2000); that introduction also summarizes the basic physics and provides many additional references to the literature on the physics of Photo-Dissociation Regions (PDRs).

With the exception of the most recent work on M101, the studies referenced above have been carried out on relatively coarse linear scales, typically 500 - 1000 pc. This is too coarse to even begin to resolve the morphology of individual PDRs, which form “blankets” and “blisters” on the surfaces of GMCs with the largest scales of ~ 100 pc. Such structures were first identified in M81 with a resolution of ~ 150 pc (Allen et al. 1997) and in M101 with a resolution of ~ 220 pc (Smith et al. 2000).

In this paper I want to start from the “other” end, at length scales of ~ 1 pc, and explore the nature of the HI structures associated with GMCs in the Galaxy. These structures can also be explained with the photodissociation model, and provide new information on how to quantify the relation between UV-producing B stars and HI. To give the story some structure I will describe the examples on scales of a factor of 10 from 1 to 1000 pc, providing overlap with the studies described above and showing the continuity and ubiquity of the photodissociation process in the ISM of galaxies.

3. HI associated with H_2 on the ≈ 1 pc scale

On the scale of ≈ 1 pc the radio – HI resolution is too poor to look for HI – H_2 associations anywhere except in the Galaxy, and there, confusion along the line

of sight usually makes the identification of HI features with specific stars and GMCs very difficult. Nevertheless, new all-sky HI surveys at high resolution have revealed several cases of discrete HI features associated with young stars deeply embedded in dense molecular clouds.

3.1. Deeply-embedded young stars

The prototype of this class is IRAS 23545+6508 (Dewdney et al. 1991). This object is a strong IR source and a weak radio continuum source, and also has a faint reflection nebula apparently associated with it. The HI source is compact, ≈ 0.6 pc in diameter, with $M(\text{HI}) \approx 1.4 M_{\odot}$. The star is B3 or B4 but behind $A_V \approx 11$ mag of extinction, embedded in a dense GMC at ≈ 1 kpc distance.

Several other examples like IRAS 23545+6508 have been found (Purton, private communication), including an object associated with the star BD +65 1638 in the star-forming region around NGC 7129 (Matthews et al., in preparation), IRAS 01312+6545 found in the Canadian Galactic Plane Survey, and IRAS 06084-0611 associated with BD +30 549. These are all examples of "dissociating stars" with several M_{\odot} of HI and a very small amount of ionized gas (1/1000 of the HI) surrounding B stars of types ranging from 0.5 to 5. Charles Kerton (private communication) has recently provided a list of additional candidates (Table 1). These objects all have HI masses of a few M_{\odot} .

Table 1. Additional IRAS - B-star associations.

IRAS Number	$D_{kin}(\text{pc})$	Sp. Type
01431+6232	6.0	B3
01448+6239	4.8	B3
01546+6319	6.0	B3
01524+6332	4.5	B5

The identification of these objects on HI maps of the Galactic plane is facilitated by the very compact character of their HI emission. Presently the search criterion involves a correspondence of an HI concentration with a compact source of IR emission, but the best way to find these objects in the Galaxy is still under discussion. Figure 1 shows the HI and CO(1-0) emission identified with IRAS 01431+6232.

Table 1 is likely to be affected by observational selection. For instance, the HI emission from such objects which are closer to us will be larger in angular size and more diffuse, and therefore increasingly difficult to discern in the HI maps; on the other hand, at distances of a few kpc, these objects are barely resolved, so more distant HI objects will be fainter and offer less contrast with the ambient HI. The concentration to mid-B spectral types may also be a selection effect; later-type stars produce too little dissociating radiation, so not enough HI is produced, whereas the ionizing flux from earlier-type stars destroys the HI, creating a substantial HII region instead.

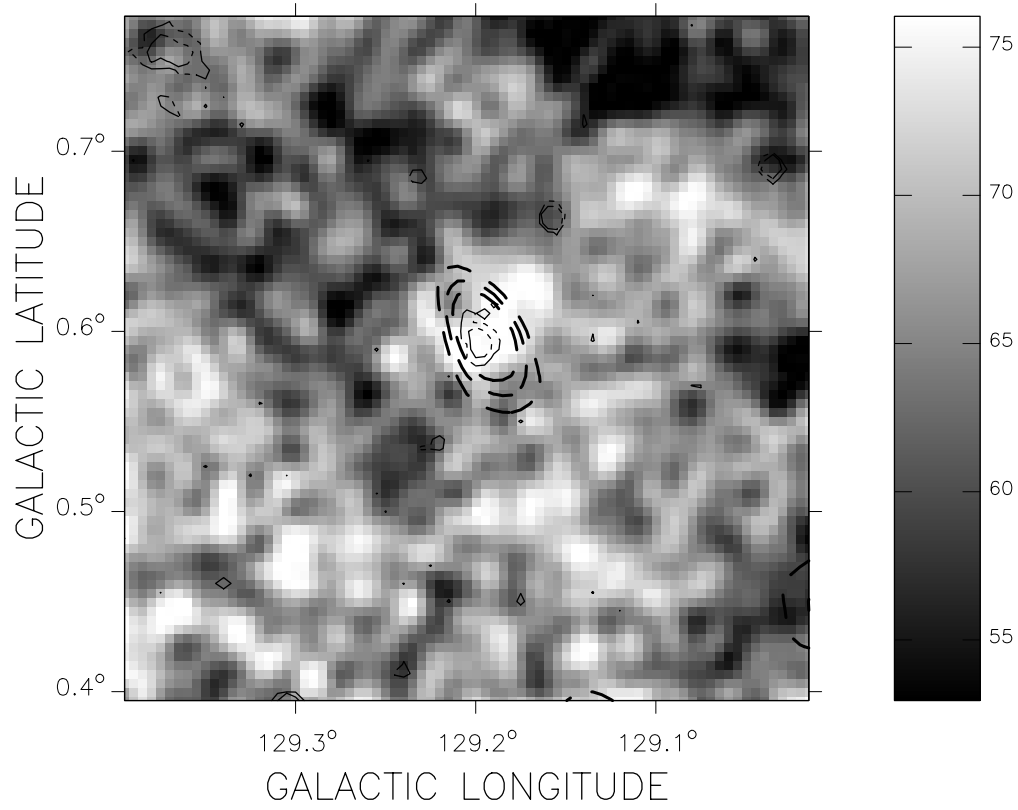


Figure 1. Emission associated with IRAS 01431+6232. The greyscale is HI emission from 53-76 K; the outer dashed contours are CO emission at 0.4, 0.6 and 0.8 K km s⁻¹; and, the inner contours are MSX Band A infrared emission at 1×10^6 and 2×10^6 Watts m⁻² sr⁻¹. Figure courtesy Charles Kerton, DRAO.

3.2. The dissociated HI mass; a simple calculation

The central star e.g. in IRAS 23545+6508 has $T_{\text{eff}} \approx 17,000 - 18,000$ K, so the rate of production of ionizing photons is $\mathcal{R}_{\text{LYC}} \approx 10^{43.3}$ photons/sec. But the rate of production of *dissociating* photons is much higher, $\mathcal{R}_{\text{FUV}} \approx 10^{46.5}$ photons/sec (e.g. Puxley et al. 1990) in the range $912 < \lambda < 1108$ Å.

According to Dewdney et al. (1991) the GMC density $n_2 \approx 900$ molecules cm^{-3} , so the $2 \times \text{HI} \rightarrow \text{H}_2$ reformation time on grains $\tau_{\text{rec}} \approx 3.3 \times 10^8 / n_H$ years is $\approx 1.8 \times 10^5$ yr for $n_H = n_1 + 2n_2$, significantly longer than the estimated present age of the B star of $\tau_{\text{B3V}} \approx 10^4$ yr. In this case a simple calculation can be made of the total mass of dissociated HI around the star. Assuming that 100% of the dissociating photons produced are used inside the GMC, and taking the efficiency $\eta \approx 0.15$ for the dissociation of an H_2 molecule into two HI atoms, the number \mathcal{N} of HI atoms produced by the star up to the present time is:

$$\begin{aligned} \mathcal{N}(\text{HI}) &= 2 \times \eta \times \mathcal{R}_{\text{FUV}} \times \tau_{\text{B3V}}, \\ &\approx 3 \times 10^{57} \text{ HI atoms}, \\ M &\approx 2.5 M_{\odot} \text{ of HI.} \end{aligned}$$

The excellent agreement with the observed value of $1.4 M_{\odot}$ must be fortuitous, considering the approximations. Dewdney et al. (1991) used a more complete, time-dependent model of HI production they developed themselves (Roger & Dewdney 1992) to arrive at a value of $2 - 3 M_{\odot}$ of HI, again assuming a lifetime of 10^4 yr for the star.

Note that if the volume density of the molecular ISM in which these stars are embedded was lower, say $n_2 \approx 100 \text{ cm}^{-3}$ (the typical GMC), the HI sources would be ≈ 10 pc in size (with the same HI mass of a few M_{\odot}), and would begin to merge into the generally-lumpy distribution of Galactic HI, making them even more difficult to identify.

4. HI associated with H_2 on the ≈ 10 pc scale

On the ≈ 10 pc scale in the Galaxy, confusion is a major problem, and specific associations of HI and H_2 have been made only in cases where the geometry is particularly simple, or the region is not confused by other features along the line of sight (e.g. at high Galactic latitude).

4.1. HI and H_2 in interstellar cirrus clouds

A study of the HI, CO, and IR emission from a sample of 26 isolated, high-Galactic-latitude cirrus clouds (Reach, Koo, & Heiles 1994) with typical sizes 1 - 10 pc shows that the H_2 content of these clouds is of the same order as the HI mass, in spite of their location above the Galactic plane where we might expect the UV flux from the Galaxy to have destroyed all the H_2 . In one well-studied case (G236+39) the inferred mass of H_2 is $70 M_{\odot}$, compared to an HI mass of $90 M_{\odot}$.

4.2. Warm HI “envelopes” around Galactic GMCs

An analysis of observations of several Galactic GMCs (Andersson & Wannier 1993 and references there) reveals warmed HI surface layers with characteristic

depths of ≈ 2 pc and maximal extents of ≈ 10 pc. The HI production is ascribed to photodissociation. In one well-studied case (Andersson, Roger, & Wannier 1992) the envelope around the GMC called “B5” in the Per OB2 association has $350 M_{\odot}$ of HI in an envelope which is moderately dense, $\approx 35 \text{ cm}^{-3}$, and warm, ≈ 70 K, and is expanding away from the cloud at approximately the escape velocity. Blitz & Terndrup (quoted in Blitz 1993) have reported on about a dozen cases of HI envelopes surrounding Galactic GMCs in or near well-known star-forming regions (NGC 7023, S140, Per OB2, Orion, ...). The HI masses range from ≈ 500 to $500,000 M_{\odot}$.

4.3. Another simple calculation

How much HI could be produced by photodissociation around a typical GMC embedded in the mean interstellar radiation field (ISRF)? For this estimate our initial approach assuming a very young PDR and neglecting re-formation of H_2 will not be adequate. We need a steady-state calculation, where the HI production rate by photodissociation of H_2 is balanced by the $2 \times \text{HI} \rightarrow \text{H}_2$ reformation rate on grain surfaces. We use the model developed by Sternberg (1988) to determine the steady-state column density of HI. For standard values of ISM parameters in the solar neighborhood we have:

$$N(\text{HI}) \approx 5 \times 10^{20} \times \ln(90\chi/n_{\text{H}} + 1)$$

where:

$$\begin{aligned} N(\text{HI}) &= \text{the HI column density in atoms cm}^{-2}, \\ \chi &= \text{the FUV intensity relative to the local ISRF, and} \\ n_{\text{H}} &= \text{the total proton volume density of the gas.} \end{aligned}$$

The standard GMC has a diameter of 50 pc, an average H_2 volume density $\langle n_2 \rangle \approx 100$ and a total mass of $10^{5-6} M_{\odot}$ (Blitz 1993). The ISRF therefore creates a “skin” of HI on the surface of this cloud with $N(\text{HI}) \approx 3.5 \times 10^{20}$ atoms cm^{-2} . Assuming the cloud is spherical, its surface area is $7 \times 10^{40} \text{ cm}^2$, so the warm HI envelope around the GMC will contain:

$$\begin{aligned} \mathcal{N}(\text{HI}) &\approx 3.5 \times 10^{20} \times 7 \times 10^{40} \text{ HI atoms, which is} \\ M(\text{HI}) &\approx 2.1 \times 10^4 M_{\odot} \text{ of HI,} \end{aligned}$$

...close to the average observed HI mass in the GMC sample of Blitz & Terndrup. Such GMCs are apparently about 10% HI and 90 % H_2 .

5. HI associated with H_2 on the ≈ 100 pc scale

On the ≈ 100 pc scale in the Galaxy, confusion remains a big problem. Unusual morphologies, correspondences in several tracers, and careful isolation of features along the line of sight are necessary.

5.1. HI “tails” and “cones”

The Canadian Galactic Plane Survey in HI and radio continuum, coupled with a similar coverage in CO emission with the FCRAO radio telescope, has revealed

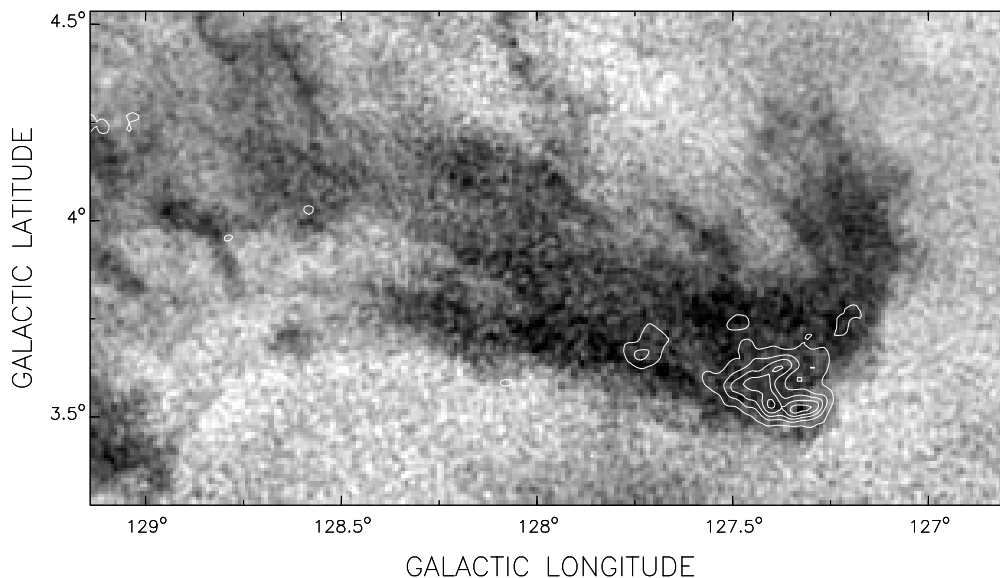


Figure 2. HI and CO(1-0) emission associated with WK-7. The greyscale is HI emission from 0-40 K; the contours are CO(1-0) emission at 0.3, 0.8, 1.3, 1.8, 2.3, and 2.8 K km s⁻¹. Figure courtesy Lewis Knee, DRAO.

many features in the Galaxy which bear the signature of the destruction of GMCs by photodissociation (e.g. Wallace & Knee 1999). The object WK-7 is a typical example (Figure 2), with CO emission at the apex of an HI structure that fans out away from the CO. For many of these associations B stars have been found nearby.

5.2. Maddelena’s cloud

A careful separation of features in radial velocity has permitted the identification of a large ($\approx 50 \times 200$ pc), “blanket” of HI located in the Galaxy and associated with CO emission from the GMC G216-2.5 (Williams & Maddelena 1996) and two nearby young stars (at least one of which is surely a B star). This structure is especially important to the discussion now because it is large enough to be identified in high-resolution HI studies of nearby galaxies, and shows us the morphology we ought to be seeking in that case. An interesting point with this object is that both the HI and the CO emission from this structure appear roughly to fit into the PDR picture. The observations give the “excess” HI associated with the PDR as $\approx 2 \times 10^{20}$ atoms cm⁻² and the average CO(1-0) intensity as ≈ 6 K km s⁻¹. These two points are in rough agreement with the combined predicted CO(1-0) (Kaufman et al. 1999) and HI intensity (equation given above) for an H₂ density of ≈ 100 cm⁻³, typical for GMCs in the Galaxy (Blitz 1993), and for an incident FUV flux of $\chi \approx 1$, which is just the estimated “excess” value coming from the nearby B stars according to Williams & Maddelena. A more refined model is under construction (Allen, Heaton, & Kaufman, in preparation).

5.3. The step to nearby galaxies

With its ≈ 100 pc size scale, Maddalena’s Cloud provides a vital link between the structures we have so far been discussing in the Galaxy and the structures we can discern in the nearby galaxies with current instrumentation. HI “blankets” and “blisters” similar in structure to Maddalena’s Cloud and characteristic of large-scale PDR morphology have now been found all over the disks of two nearby galaxies, M81 and M101, thanks to the availability of FUV imaging from the ASTRO/UIT missions and high-resolution HI images from the VLA. The combination permits a comparison of the FUV and HI morphologies on a $\approx 100 - 200$ pc scale. Although even better linear resolution would be highly desirable, there are three important advantages of working on nearby galaxies:

- The line-of-sight confusion problem which plagues the Galactic work is now virtually absent, so the features are more easily identified.
- The distances to different structures are all very nearly the same, so we do not have to contend with widely varying angular scales on the sky for what are basically the same physical structures just seen at very different distances (e.g. a given physical structure in the Local arm of the Galaxy can be 10 or more times the angular size of the same structure in the Perseus arm). The observational selection effects are therefore more nearly the same over the whole of the galaxy disk.
- Observational selection effects act to enhance the utility of HI for detecting the PDRs arising when low-density GMCs are illuminated by modest FUV radiation fields...the HI features in this case are generally larger, so the telescope beam filling factors are larger, and the HI is therefore easier to detect on the 21-cm VLA maps.

FUV and HI in the Sb I-II spiral M81 HI “blisters” and “shells” are common in M81 (Allen et al. 1997) and are clearly associated with nearby clusters of young stars. These clusters sometimes also emit $H\alpha$, but not always, whereas the association with HI is common; B stars dominate the FUV morphology at $\lambda 150$ nm. In addition to the association of discrete HI and FUV features in M81, the general FUV brightness correlates well with the HI brightness in spiral arms (more on this later), indicating that HI production by a general, scattered distribution of dissociating stars is important.

FUV and HI in the Sc I spiral M101 In the first really detailed, quantitative study of the HI – FUV association, Smith et al. (2000) have developed a method using the equations given earlier in this paper to discover a new probe for the molecular gas in galaxies. They conclude that GMCs in M101 have volume densities in the range of $30 - 1000 \text{ cm}^{-3}$ with no clear trend from the inner to the outer parts of the galaxy. The large-scale and well-known decrease in $N(\text{HI})$ in the inner parts of M101 is explained in the context of their PDR model as a result of the increasing dust/gas ratio there.

6. HI associated with H₂ on the ≈ 1 kpc scale

On the ≈ 1 kpc scale in nearby galaxies the individual PDRs can not be resolved, and we must make do with trying to interpret the general surface brightness distributions of FUV and HI. A recent result in the outer parts of M31 bridges the gap, providing a clear association between a general distribution of identified B stars and the associated (low-resolution) HI surface brightness.

6.1. Gas, dust, and young stars in the outer disk of M31

Cuillandre et al. (2001) have studied a field in the far outer parts of M31, beyond the De Vaucouleurs radius along the major axis of the galaxy to the south-west. Besides other results in that paper we note the following points of interest here:

- There is dust mixed in with the HI on the large scale, so we may expect that H₂ is also present.
- Young stars are distributed generally with the HI. These stars have the signatures (V mag, V-I colors) of B stars in the outer parts of M31.
- These B stars are found at radial distances of 23 to 33 kpc (4 to 5.7 times the disk scale length in B) in areas where the galaxy optical surface brightness is $\mu_B > 27$ mag arcsec⁻². This is approaching the range of a low-surface-brightness galaxy.
- Faint H α emission has very recently been detected from some of the richest concentrations of bright MS stars, confirming the interpretation that these are mostly B stars (Cuillandre, private communication).
- Computations of the FUV output from the census of observed B stars and a fit of the data to PDR models is under way; preliminary results are encouraging and give reasonable values for the densities of the GMCs which must be the antecedents of the B stars.

6.2. FUV and HI surface brightness correlations in M81

A general correlation of VLA-HI and UIT-FUV surface brightness on the ≈ 1 kpc scale has very recently been shown in M81 (Emonts et al., in preparation). Figure 3 shows this correlation when the data is smoothed to $\approx 1'$. The results are consistent with a photodissociation model, although the precise parameters (e.g. the H₂ volume density) are uncertain owing to the averaging procedure on the model. The correlation is closely similar to that determined for a sample of nearby galaxies from the FAUST Far-UV survey (Deharveng et al. 1994), although the interpretation is quite different; this particular result and its relation to the subject of the global star formation rate in galaxies is discussed in more detail by Allen (2002).

6.3. Yet another simple calculation

What fraction of the total HI in a galaxy is maintained by the photodissociation process we have been discussing here? As an example, let's take the case of NGC 4152, an Sc galaxy at $D \approx 19.5$ Mpc in Virgo. The FAUST Far-UV

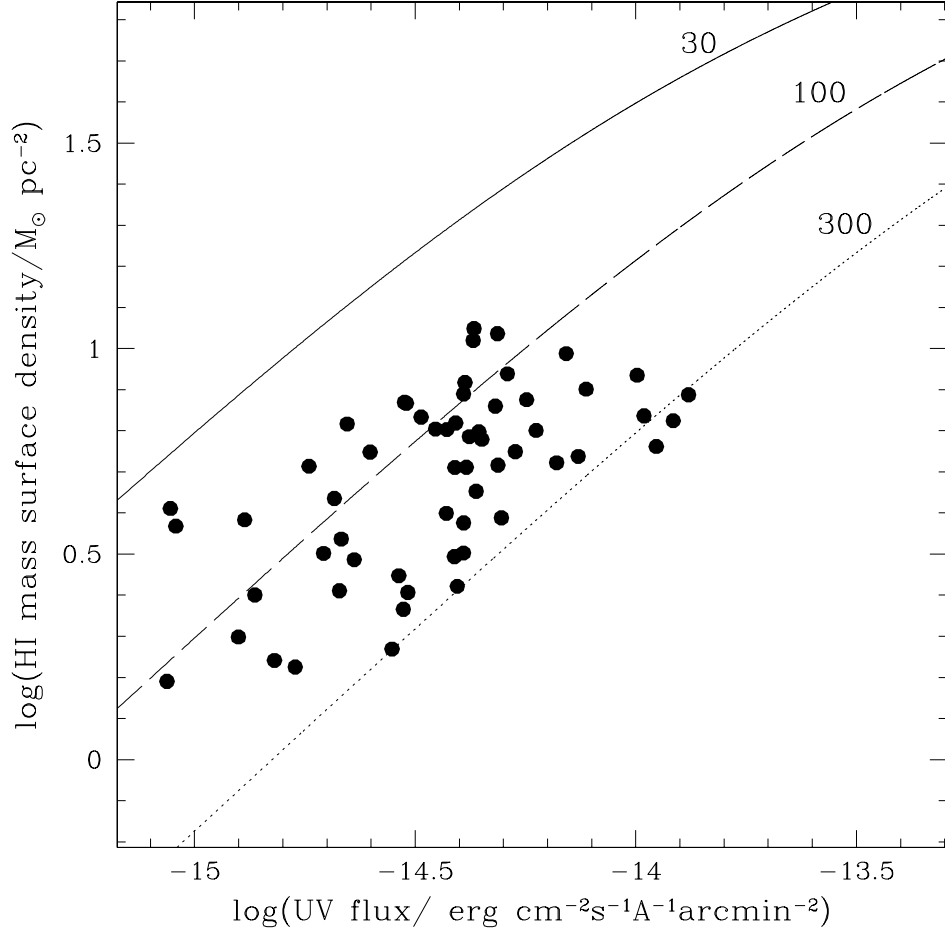


Figure 3. Global comparison of HI mass surface density and FUV surface brightness at individual locations in the galaxy M81 at an angular scale of $\approx 1'$. From Emonts et al. (in preparation). The curves are from a simple photodissociation model which is only very approximate at the moment; a more complete calculation is in progress.

flux is 6.3×10^{-14} ergs/cm²/sec/Å (Deharveng et al. 1994) at $\lambda \approx 1500$ Å. This corresponds to about 1 photon/cm²/sec at earth, or $\approx 4 \times 10^{52}$ Far-UV photons/sec at the galaxy. Let us take the fraction trapped in the galaxy to be f_t . What is the appropriate time scale? This depends of course on the reformation time for the process $2 \times \text{HI} \rightarrow \text{H}_2$ on grains, which we mentioned briefly earlier in this talk. If we take a typical GMC volume density to be $n_2 \approx 5 - 50$ H₂ molecules cm⁻³, the reformation time is typically $3 \times 10^{6-7}$ yr for standard dust parameters. The Far-UV photon production rate in NGC 4152 then accounts for:

$$2 \times 0.15 \times f_t \times 4 \times 10^{52} \times 3 \times 10^{6-7} \times 3 \times 10^7 \approx f_t \times 10^{66-67} \text{ HI atoms.}$$

A typical value for $f_t \sim 0.5$, and this galaxy contains $2.08 \times 10^9 M_\odot$ of HI, or 2.5×10^{66} HI atoms. So from 20% – 200% of the HI present could be accounted for by photodissociation! This result is startling, and perhaps even a bit outrageous; a more precise calculation is now clearly required.

7. Conclusions

- The *morphology* of HI features near Far-UV sources in disk galaxies is consistent with that expected for (low-density) PDRs.
- The *quantity* of HI in these features can be calculated using simple photodissociation physics.
- The *distribution* of HI, even at faint levels, can be explained for the most part as a steady-state photodissociation – reformation process of $\text{H}_2 \rightleftharpoons 2 \times \text{HI}$, where the Far-UV photons come mainly from non- or only weakly-ionizing B stars, and the reformation occurs on the surfaces of dust grains.

These conclusions raise two very important questions, still unanswered:

1. Just how much H₂ does a typical galaxy contain?
2. How much of the HI in these galaxies is primordial?

The hints at answers provided by the work reviewed in this talk suggest that significantly more H₂ is present than we currently suspect, and that the HI clouds in the ISM of galaxies may be mostly “processed” gas.

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Discussion

Silk: Your account of the origin of the HI by photodissociation should scale to Low Surface Brightness (LSB) galaxies. What is the status of searching for the evidence for your ideas in these systems?

Allen: The basic idea here is that B stars ought to *always* accompany HI, so they ought to be present even in the LSB disks. In general, one needs HST to detect upper-main-sequence stars, and only a small number of LSB galaxies are nearby enough to make this feasible. In fact Ken and I have tried to obtain HST time for such work, but we have not been successful. However, I understand that the classic LSB galaxy NGC 2915 is on the program for HST observations in guaranteed time with the new Advanced Camera; this galaxy is near enough,

and there is enough known about the detailed distribution of HI, that the results ought to be clear.

Harding: What is the source of the primordial H_2 if it is the source of gas for star formation and for HI production?

Allen: This question is in the realm of cosmology and galaxy formation, and I don't really know much about those subjects. I hear that some of the latest work on galaxy formation shows that H_2 could be formed at an early epoch from primordial HI and H^+ by reactions that do not require dust. The reaction rates are slow, but on the other hand there is lots of time.

Bosma: There is a lot of HI around the galaxy NGC 3077 in the M81 group. According to your ideas, there should be UV emission associated with it. Did you look for this, and did you detect anything?

Allen: The UIT field containing M81 does not extend out to NGC 3077, so we can not do the check you describe. However, the field does indeed include some of the HI "streamers" located in the far outer parts of M81 to the east, in the general direction of NGC3077. My student Mr. Emonts has recently produced $1'$ smoothed versions of the HI and FUV images, and there is indeed detectible FUV emission associated with this "bridge" HI. We are looking more closely at this result, but at first sight the correlation between HI and FUV emission seems to agree with the general trend shown in Figure 3 of my talk.

King: There's an implication here that you didn't state outright. There's got to be a reservoir from which future stars will be made; are you saying this is H_2 rather than HI?

Allen: I think the conventional wisdom is that star formation, at least for stars of masses less than a few M_\odot , requires "processed" gas containing heavy elements and dust as the raw material. Such "stuff" turns molecular relatively quickly compared, for example, to the rotation time of a galaxy. So indeed it is likely that the reservoir of gas required for future generations of star formation will be molecular, and the HI we see is a photodissociation product of the star formation process itself. This suggests that galaxies have a larger reservoir of H_2 than we think they do, but unfortunately I don't yet know how to calculate how much!